Observation of magnon polarons in van-der-Waals itinerant ferromagnet Fe_3GeTe_2

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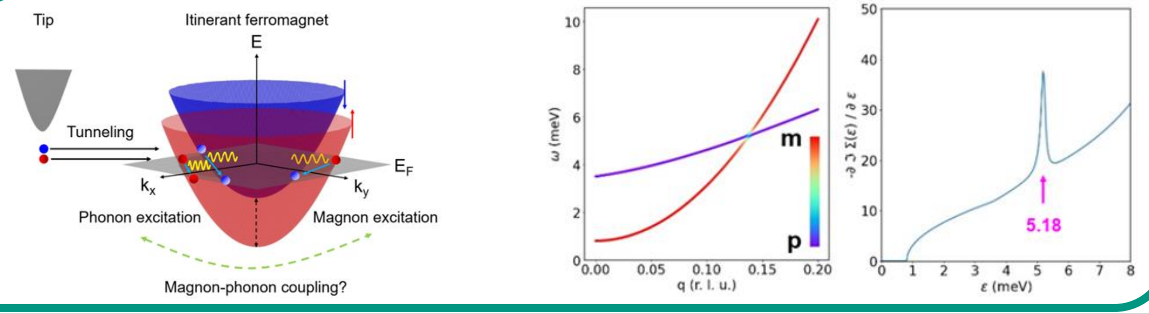

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Collaborations and acknowledgements

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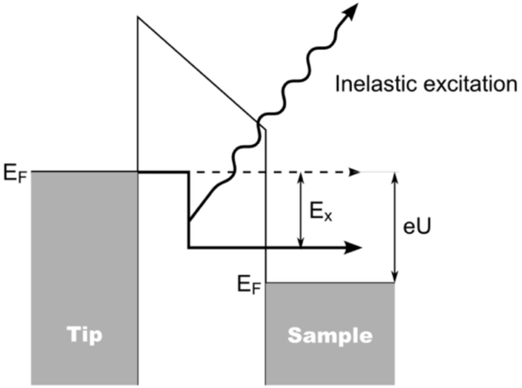
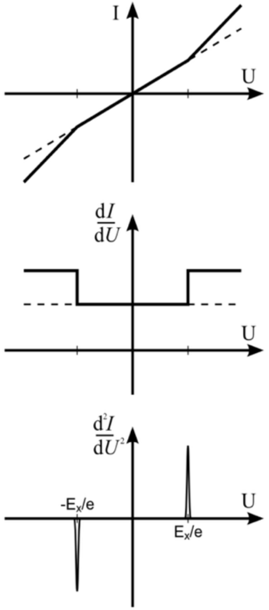
Inelastic scanning tunneling spectroscopy (ISTS)

Sketch of ISTS





Microscopically, the inelastic process is encoded in the imaginary part of electron self-energy, whose energy derivative contributes directly to the spectroscopic features observed in ISTS.

$$\frac{d^2 I}{dU^2} \propto -\frac{\partial \operatorname{Im}\Sigma(\omega)}{\partial \omega}$$

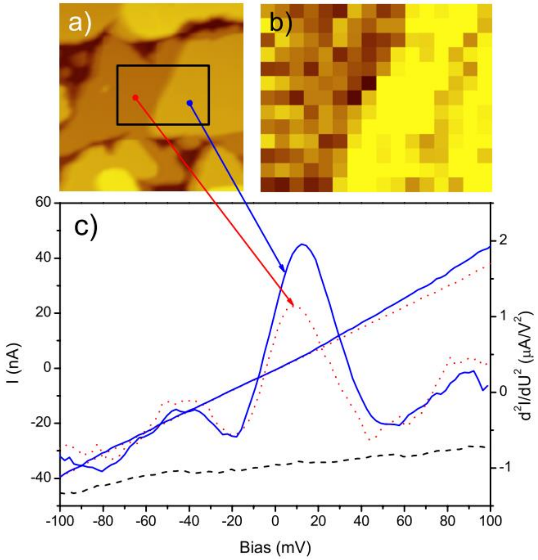
Applications of ISTS

Timeline	ISTS application	Reference
1986	Phonon excitations	Smith et al., Appl. Phys. Lett. 49, 1641 (1986).
1998	Molecular vibrations	Stipe et al., Science 280, 1732 (1998).
2004	Single-atom spin excitations	Heinrich et al., Science 306, 466 (2004).
2006	Magnon excitations	Balashov et al., Phys. Rev. Lett. 97, 187201 (2006).

E. L. Wolf, Principles of Electron Tunneling Spectroscopy (Oxford University, New York, 1985), pp. 339–348.

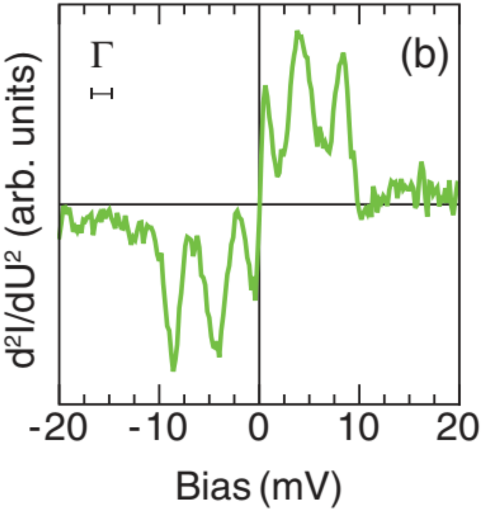
What will happen with magnon-phonon coupling?

Magnon excitation:
Co thin films on Cu(111)



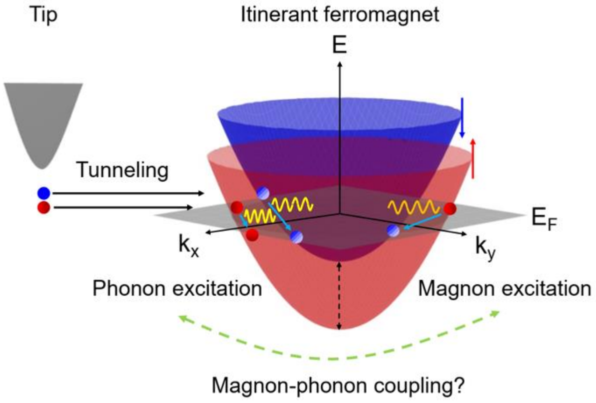
T. Balashov, A. F. Takacs, W. Wulfhekel, and J. Kirschner, PRL 97, 187201 (2006).

Phonon excitation:
Pb thin films on Cu(111)



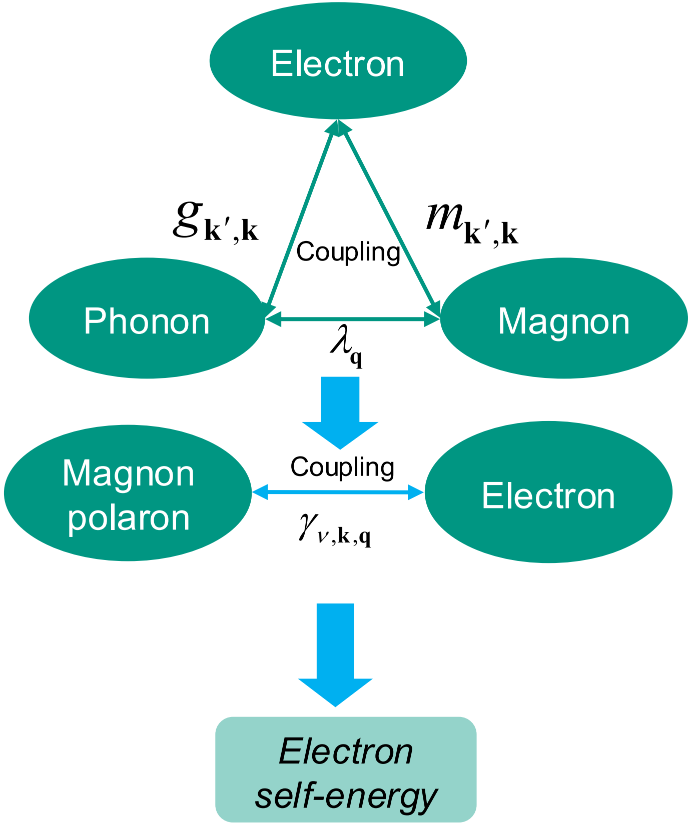
M. Schackert, …, W. Wulfhekel, PRL 114, 047002 (2015).

Excitation with magnon-phonon coupling?



Q. Li, …, Wulf Wulfhekel, Nat. Commun. 17, 5461 (2026).

ISTS model for magnon polaron



Hamiltonian

$$H_{sample} = \sum_{\mathbf{k}\sigma} \varepsilon_{\mathbf{k}\sigma} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{\mathbf{q}} h\omega_p a^{\dagger}_{\mathbf{q}} a_{\mathbf{q}} + \sum_{\mathbf{q}} h\omega_m b^{\dagger}_{\mathbf{q}} b_{\mathbf{q}} + \sum_{\mathbf{k},\mathbf{q},\sigma} g_{\mathbf{k},\mathbf{q}} c^{\dagger}_{(\mathbf{k}+\mathbf{q})\sigma} c_{\mathbf{k}\sigma} \left(a_{\mathbf{q}} + a^{\dagger}_{-\mathbf{q}}\right) + \sum_{\mathbf{k},\mathbf{q}} m_{\mathbf{k},\mathbf{q}} \left(c^{\dagger}_{(\mathbf{k}+\mathbf{q})\uparrow} c_{\mathbf{k}\downarrow} b_{\mathbf{q}} + c^{\dagger}_{(\mathbf{k}+\mathbf{q})\downarrow} c_{\mathbf{k}\uparrow} b^{\dagger}_{-\mathbf{q}}\right) + \sum_{\mathbf{q}} \lambda_{\mathbf{q}} \left(a_{\mathbf{q}} + a^{\dagger}_{-\mathbf{q}}\right)\left(b_{\mathbf{q}} + b^{\dagger}_{-\mathbf{q}}\right).$$

Effective Hamiltonian

$$H_{sample} = \sum_{\mathbf{k}\sigma} \varepsilon_{\mathbf{k}\sigma} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{\mathbf{q}} h\omega_A A^{\dagger}_{\mathbf{q}} A_{\mathbf{q}} + \sum_{\mathbf{q}} h\omega_B B^{\dagger}_{\mathbf{q}} B_{\mathbf{q}} + \sum_{\mathbf{k}\sigma,\mathbf{q}\sigma'} \left(\alpha^{\sigma\sigma'}_{\mathbf{k},\mathbf{q}} \left(A_{\mathbf{q}} + A^{\dagger}_{-\mathbf{q}}\right) + \beta^{\sigma\sigma'}_{\mathbf{k},\mathbf{q}} \left(B_{\mathbf{q}} + B^{\dagger}_{-\mathbf{q}}\right)\right) c^{\dagger}_{(\mathbf{k}+\mathbf{q})\sigma'} c_{\mathbf{k}\sigma}.$$

$$\boxed{\hat{\alpha}_{\mathbf{k},\mathbf{q}} = \begin{pmatrix} g_{\mathbf{k},\mathbf{q}} u_{\mathbf{q}} & m_{\mathbf{k},\mathbf{q}} v_{\mathbf{q}} \\ m_{\mathbf{k},\mathbf{q}} v_{\mathbf{q}} & g_{\mathbf{k},\mathbf{q}} u_{\mathbf{q}} \end{pmatrix}, \hat{\beta}_{\mathbf{k},\mathbf{q}} = \begin{pmatrix} -g_{\mathbf{k},\mathbf{q}} v_{\mathbf{q}} & m_{\mathbf{k},\mathbf{q}} u_{\mathbf{q}} \\ m_{\mathbf{k},\mathbf{q}} u_{\mathbf{q}} & -g_{\mathbf{k},\mathbf{q}} v_{\mathbf{q}} \end{pmatrix}.}$$

Electron self-energy

$$\Sigma(\varepsilon) = \sum_{k\sigma,q\sigma'}^{\nu} \int \frac{d\omega}{2\pi} |\gamma^{\sigma\sigma'}_{\nu,k,q}|^2 G^{\sigma'}(k-q, \varepsilon-\omega) D(q,\omega).$$

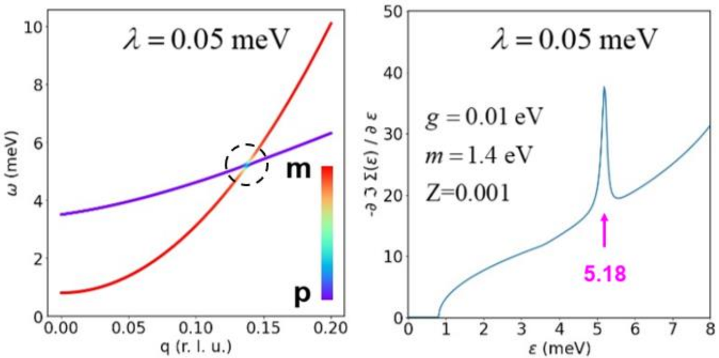
$$\hat{\gamma}_{A,\mathbf{k},\mathbf{q}} = \hat{\alpha}_{\mathbf{k},\mathbf{q}}, \hat{\gamma}_{B,\mathbf{k},\mathbf{q}} = \hat{\beta}_{\mathbf{k},\mathbf{q}}$$

$d^2I/dU^2 \propto$

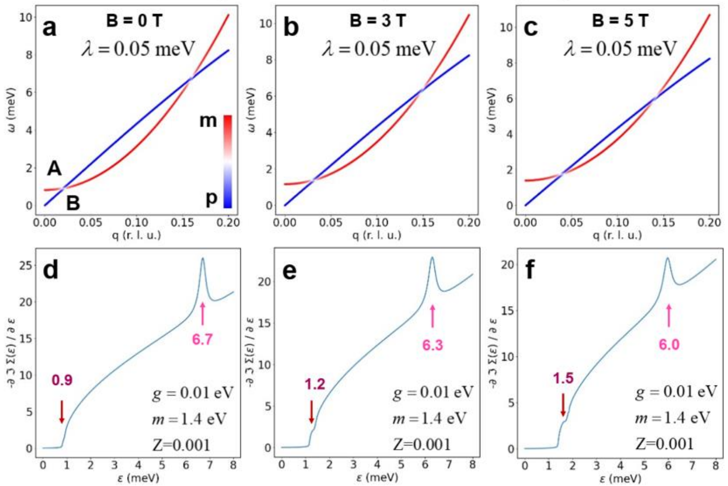
$$\boxed{-\partial \Im\Sigma(\varepsilon)/\partial\varepsilon \approx \mathrm{sgn}(\varepsilon) \sum_{\nu,\sigma} [|\gamma^{\sigma,\sigma}_{\nu}|^2 N^{\sigma}(E_F) + |\gamma^{\sigma,\bar{\sigma}}_{\nu}|^2 |Z^{\sigma,\bar{\sigma}}| N^{\bar{\sigma}}(E_F)] F_{\nu}(\varepsilon).}$$

Principle of detecting magnon polarons

Magnon-phonon coupling opens extra tunneling channels for electrons.



Magnon-acoustic phonon coupling

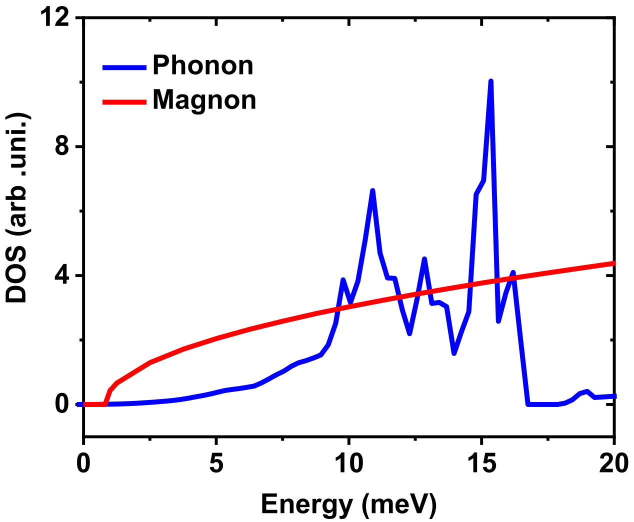


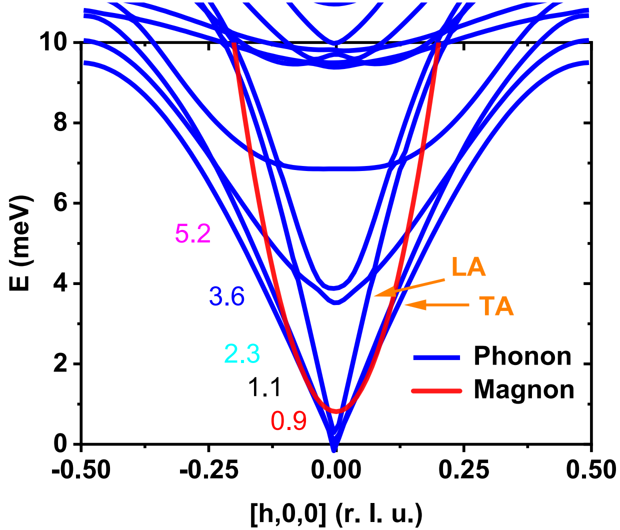
Principle of detecting magnon polarons:

1. Magnon polarons result peaks at magnon-phonon band crossings in ISTS;
2. Magnon polarons show spin dependence in spin-polarized ISTS;
3. Magnon polarons have magnon and phonon dispersions related magnetic field dependence.

Why Fe_3GeTe_2?

1. No DOS peaks for magnon and phonon below 5 meV.
2. Magnon-phonon coupling reported by theory [1] and Raman spectroscopy [2].
3. Many magnon-phonon band crossings at low energy.



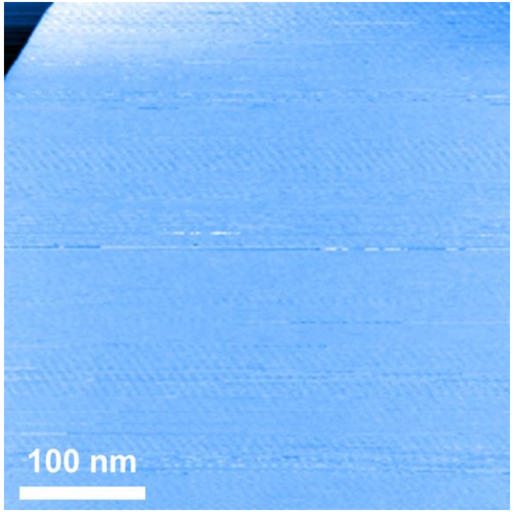


[1] Zhuang et al., Phys. Rev. B 93, 134407 (2016). [2] Du et al., Adv. Funct. Mater. 29, 1904734, (2019).

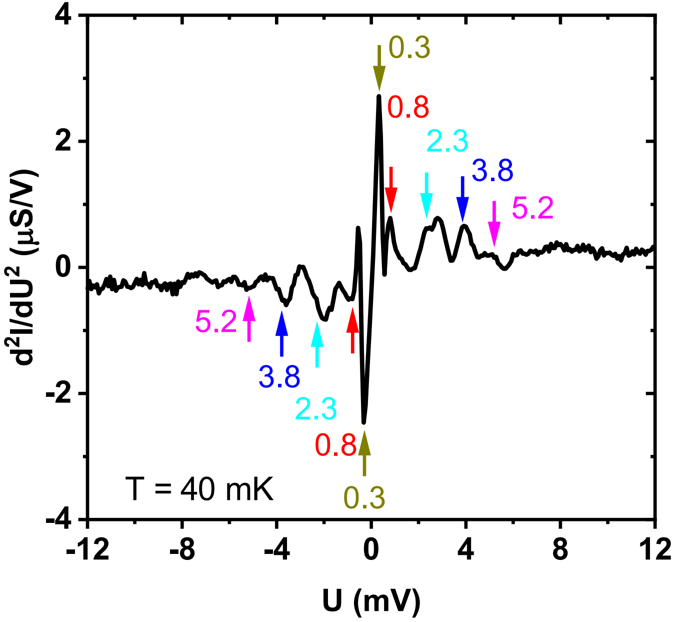
Excitations in Fe_3GeTe_2

Karlsruhe Institute of Technology

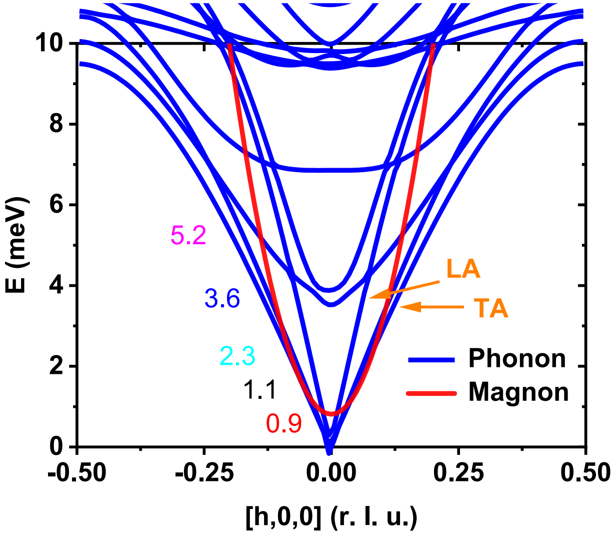
STM topography



d^2I/dU^2



Peak at 0.3 meV is due to dynamical Coulomb blockade [1].



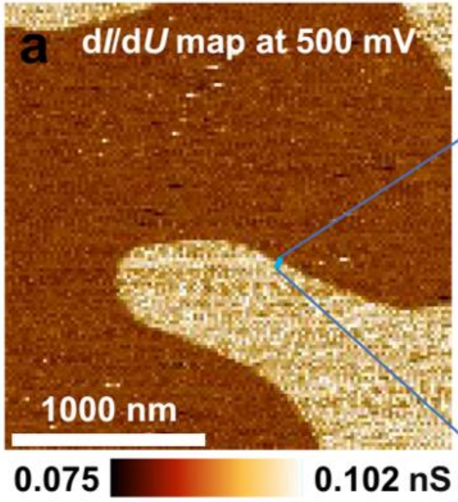
Phonon band from DFPT calculation, and magnon band from inelastic neutron scattering [2].

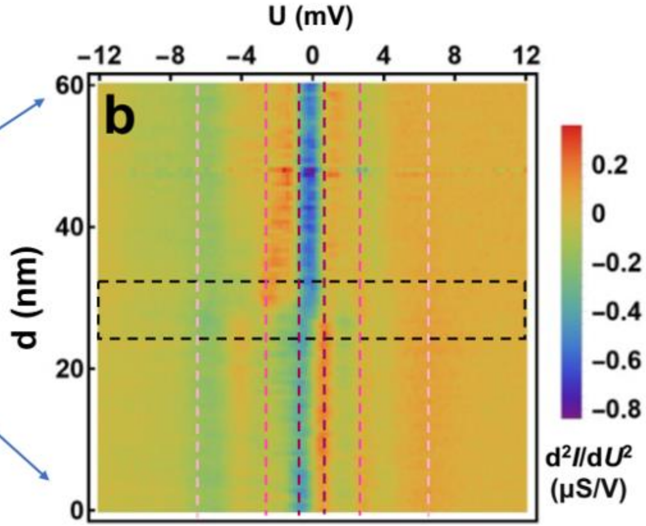
[1] Jacob Senkpiel et al., Phys. Rev. Lett. 124, 156803 (2020). [2] Bao, S. *et al., Phys. Rev. X* **12**, 011022, (2022).

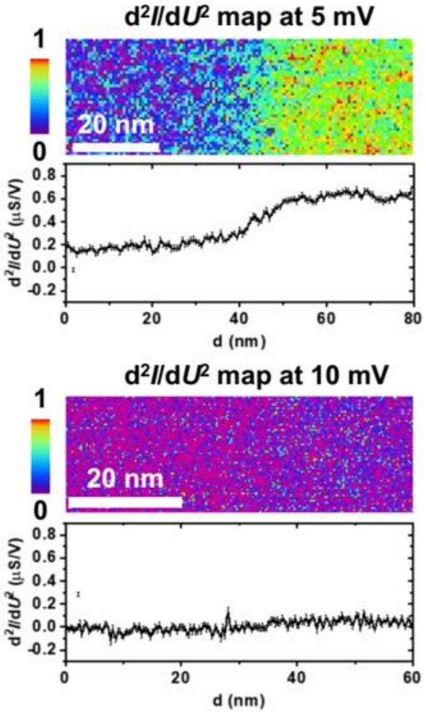
Spin dependence

Spin-polarized dI/dU map

ISTS across domain wall



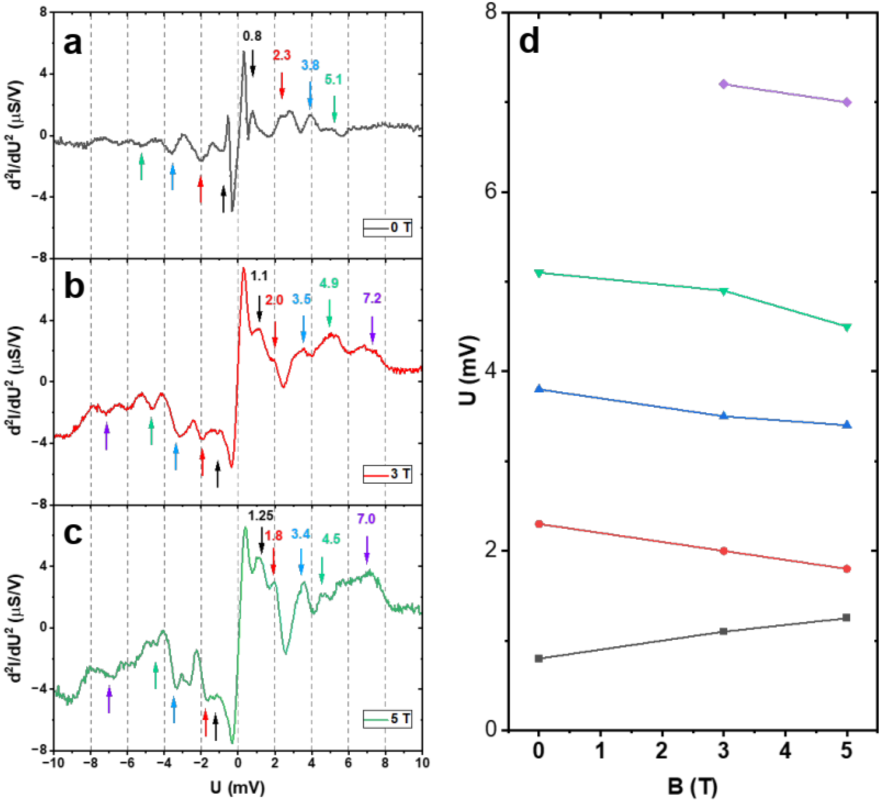




ISTS map across domain wall

➢ SP-ISTS results reveal magnetic nature of these excitations.

Magnetic field dependence



- The lowest peak shifts to higher energy with increasing magnetic field.
- Other peaks shift to lower energy with increasing magnetic field.

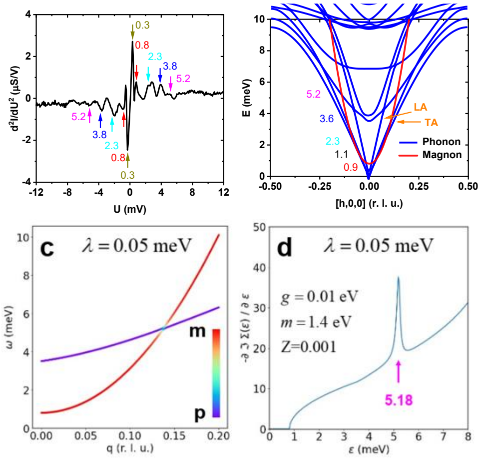
Summary

Detection of magnon polarons by ISTS:

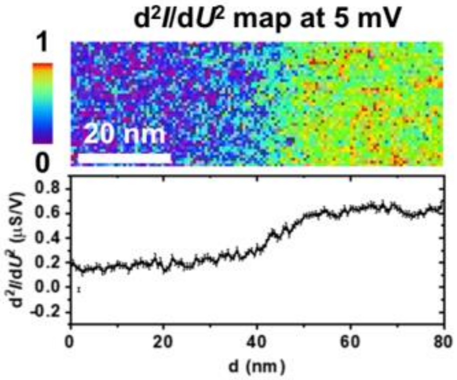
1. Excitations in ISTS matching the magnon-phonon band crossings;
2. Spin dependence in SP-ISTS;
3. Magnetic field dependence determined by magnon and phonon dispersions.

Only when the above three conditions are satisfied, we can claim the observation of magnon polaron.

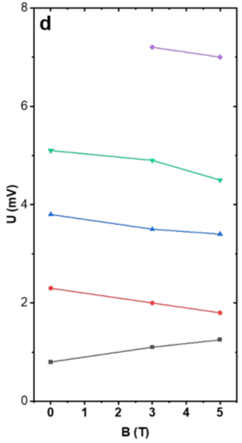
1. Excitations



2. Spin dependence



3. Magnetic field dependence



More details

Q. Li, N. Bansal et al., Nat. Commun. 17, 5461 (2026).

Thank you for your attention